Jefferson Lab PAC18
Proposal Cover Sheet

JLAB USER GROUP

This document must be received by close of business Thursday, June 1, 2000 at:

Jefferson Lab
User Liaison,
Mail Stop 12B
12000 Jefferson Ave.
Newport News, VA
23606

Experimental Hall: B
Days Requested for Approval: 7

❒ **Proposal Title:**
Channeling Radiation from GeV Electrons in Diamond

Proposal Physics Goals
Indicate any experiments that have physics goals similar to those in your proposal.

Approved, Conditionally Approved, and/or Deferred Experiment(s) or proposals:

Contact Person

Name: B. L. Berman
Institution: George Washington University
Address: Department of Physics
Address: 725 21st St. NW
City, State, ZIP/Country: Washington, DC 20052 / USA
Phone: (202) 994-7192 **Fax:** (202) 994-3001
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Jefferson Lab Use Only

Receipt Date: 6/1/00
By: [redacted]

PR 00-109

HAZARD IDENTIFICATION CHECKLIST

JLab Proposal No.: ____________________ Date: 6/1/00
(For CEBAF User Liaison Office use only.)

Check all items for which there is an anticipated need.

Cryogenics _____ beamline magnets _____ analysis magnets _____ target type: _____ flow rate: _____ capacity: _____	**Electrical Equipment** _____ cryo/electrical devices _____ capacitor banks _____ high voltage _____ exposed equipment	**Radioactive/Hazardous Materials** List any radioactive or hazadorous/toxic materials planned for use: _____ _____ _____ _____
Pressure Vessels _____ inside diameter _____ operating pressure _____ window material _____ window thickness	**Flammable Gas or Liquids** type: _____ flow rate: _____ capacity: _____ **Drift Chambers** type: _____ flow rate: _____ capacity: _____	**Other Target Materials** ___ Beryllium (Be) ___ Lithium (Li) ___ Mercury (Hg) ___ Lead (Pb) ___ Tungsten (W) ___ Uranium (U) ___ Other (list below) _____ Diamond
Vacuum Vessels _____ inside diameter _____ operating pressure _____ window material _____ window thickness	**Radioactive Sources** _____ permanent installation _____ temporary use type: _____ strength: _____	**Large Mech. Structure/System** _____ lifting devices _____ motion controllers _____ scaffolding or _____ elevated platforms
Lasers type: _____ wattage: _____ class: _____ Installation: _____ permanent _____ temporary Use: _____ calibration _____ alignment	**Hazardous Materials** ___ cyanide plating materials ___ scintillation oil (from) ___ PCBs ___ methane ___ TMAE ___ TEA ___ photographic developers ___ other (list below) _____ _____	**General:** Experiment Class: _____ Base Equipment _____ Temp. Mod. to Base Equip. _____ Permanent Mod. to Base Equipment _____ Major New Apparatus Other: _____ _____

LAB RESOURCES LIST

JLab Proposal No.: ____________________ Date 6/1/00

(For JLab ULO use only.)

List below significant resources — both equipment and human — that you are requesting from Jefferson Lab in support of mounting and executing the proposed experiment. Do not include items that will be routinely supplied to all running experiments such as the base equipment for the hall and technical support for routine operation, installation, and maintenance.

Major Installations *(either your equip. or new equip. requested from JLab)*

New Support Structures:

Data Acquisition/Reduction

Computing Resources:

New Software:

Major Equipment

Magnets:

Power Supplies:

Targets:

Detectors:

Electronics:

Computer Hardware:

Other:

Other:

Instrument e-counters in cross at Tagger exit.

BEAM REQUIREMENTS LIST

JLab Proposal No.: ______ Date: 6/1/00

Hall: B Anticipated Run Date: ______ PAC Approved Days: ______

Spokesperson: B L Berman
Phone: (202) 994-7192
E-mail: berman @ gwu.edu

Hall Liaison: ______

List all combinations of anticipated targets and beam conditions required to execute the experiment. (This list will form the primary basis for the Radiation Safety Assesment Document (RSAD) calculations that must be performed for each experiment.)

Condition No.	Beam Energy (MeV) (approx.)	Mean Beam Current (μA)	Polarization and Other Special Requirements (e.g., time structure)	Target Material (use multiple rows for complex targets — e.g., w/windows)	Material Thickness (mg/cm²)	Est. Beam-On Time for Cond. No. (hours)
1	2500	0.0015 to 0.15	$\frac{\Delta E}{E}$ < 0.03%	100 and 500 μm Diamond	45-225	56
2	4000	0.0015 to 0.15	Divergence < 0.05 mrad	"	"	"
3	5500	0.0015 to 0.15	Spot size 0.1 to 1.0 mm	"	"	"

The beam energies, E_{Beam}, available are: $E_{Beam} = N \times E_{Linac}$ where N = 1, 2, 3, 4, or 5. E_{Linac} = 800 MeV, i.e., available E_{Beam} are 800, 1600, 2400, 3200, and 4000 MeV. Other energies should be arranged with the Hall Leader before listing.

Computing Requirements List

Proposal Title: Channeling Radiation from GeV Electrons in Diamond

Spokesperson: B L Berman **Experimental Hall:** B

Raw Data Expected

Total: Very modest **Per Year (long duration experiments only):**

Simulation Compute Power (SPECint95 hours) Required: N/A

On-Line Disk Storage Required: Minimal

Imported Data Amount from Outside Institutions: N/A

Exported Data Amount to Outside Institutions:w Minimal

Expected Mechanism for Imported/Exported Data:

Special Requirements

For example, special configuration of data acquisition systems) that may require resources and/or coordination with JLab's Computer Center. Please indicate, if possible, what fraction of these resources will be provided by collaborating institutions and how much is expected to be provided by JLab.

Channeling Radiation from GeV Electrons in Diamond

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Abstract

We propose to study the properties of channeling radiation produced by electrons in the energy region of a few GeV passing through single crystals of diamond along its major crystalline planes and axes. The unprecedented emittance, resolution, and stability of the CEBAF machine, together with the combination of goniometer, photon tagger, and beam-profile detector system in Hall B, make possible measurements of coherent radiation at high energies that were heretofore impossible. In addition to mapping out the properties of channeling radiation as a function of various experimental parameters, we shall test the existence of nonlinear effects that have been predicted, or for which previous evidence is weak.

* Co-spokesperson
# Contact person

Introduction and Motivation

Channeling radiation, since its discovery over 30 years ago, has proven to be a very sensitive indicator of electromagnetic effects in one- or two-dimensional quantum systems. The host crystal, through which a relativistic charged particle is channeled, provides the strong electromagnetic fields needed to induce coherent radiation, and the quantum-mechanical problem is one- or two-dimensional as the channeling takes place along a crystallographic plane or axis, respectively. However, most of the previous work in this field has been performed at low or medium energies (a few MeV to a few tens of MeV), and the data obtained to date at GeV energies have been very sparse and often suffer from uncertainties owing to the experimental difficulties imposed by unstable, low-duty-cycle accelerators, and by the non-availability of the experimental apparatus necessary to do a careful and complete study of this phenomenon. The existence of CEBAF and the apparatus in Hall B now makes it possible to usher in a new era in the study of coherent-radiation effects in crystals at high energies.

When a relativistic charged particle passes through a single crystal very nearly parallel to a major crystalline plane or axis so that it is channeled in that direction, it undergoes periodic motion in the plane transverse to this direction, and hence it can radiate. Quantum mechanically, this channeling radiation corresponds to a radiative transition between two eigenstates of the transverse crystalline potential; when the transition occurs between two bound states, a sharp spectral line is emitted. When there are only two bound states (for incident low-energy electrons), or when the interplanar potential is nearly harmonic (as it is for incident positrons), the emitted radiation is nearly monochromatic. But at any incident electron energy, in the forward direction in the laboratory frame of reference, the radiation is transformed upwards in energy. In part, this is because of the relativistic velocity of the charged particle that leads to a factor of $\gamma = E/mc^2$, where E is the total energy of the particle and m is its rest mass (this can also be thought of as a deepening of the crystalline potential well by a factor of γ). The Doppler shift gives rise to an additional factor of 2γ in the forward direction. This combined factor of $2\gamma^2$ (equal to 2×10^8 for $\gamma=10^4$, corresponding to electrons or positrons of about 5 GeV, for example) brings the channeling radiation up into the interesting and useful 10-100-MeV energy region, and also makes it relatively easy to observe, using the well known methods of nuclear radiation detection. This large lever arm also makes it easy to tune channeling radiation, by varying the incident particle energy over a relatively narrow range. The same relativistic transformation folds the radiation forward in the laboratory into a narrow cone having a characteristic half-angle of $1/\gamma$ (equal to about 100 μrad in the above example), and thus makes it very intense within that solid angle. For the case of planar channeling, the radiation is linearly polarized.

In the approximation that the field source of the transverse crystalline potential can be represented by planar sheets or axial strings of charge, the particle-crystal system is equivalent to a one- or two-dimensional hydrogenic atom (for the planar and axial cases, respectively). This establishes selection rules for the radiative transitions, and enables one to predict many of the detailed properties of channeling radiation by analogy with these simple quantum-mechanical systems. In fact, the theory of channeling radiation has progressed far beyond these simple considerations, and detailed predictions of channeling-radiation spectral energies, widths, and intensities now are made routinely with the use of many-beam (i.e., many Fourier-component) calculations using wave functions deduced from electron-scattering form factors (for the atoms in the crystal) which also reflect the periodicity of the crystalline potential. Also included in modern calculations are the effects of multiple scattering, dechanneling, bremsstrahlung production, and crystal lattice vibrations.

Channeling radiation was first observed at the Lawrence Livermore Laboratory in 1968 as a low-energy enhancement in the forward radiation spectrum from 16- and 28-MeV positrons and electrons axially channeled in a silicon crystal.[1] Theoretical predictions by Kumakhov and by Terhune and Pantell in the mid-seventies[2] inspired further investigations at Livermore and elsewhere, and the first observations of spectral peaks, for both axial and planar channeling radiation, from 56-MeV positrons and electrons, were made in 1978.[3] The first observation of sharp spectral lines was made possible by very tight collimation together with the use of a diamond crystal, at Saclay in late 1980.[4] Meanwhile, channeling-radiation studies at higher energies (in the GeV region) were carried out at Tomsk, Yerevan, SLAC, Kharkov, Serpukhov, and CERN,[5] and at lower energies (a few MeV) at Albany, Illinois, Aarhus, and Darmstadt.[6] Subsequent measurements at several of these laboratories, especially at Livermore,[7] have resulted in the development of a rich literature on the subject in just a few years. The subjects studied, in addition to the characteristics of the channeling radiation itself, include (a) properties of perfect crystals, such as high-resolution mapping of the interplanar and interstring potentials, determination of Debye temperatures and thermal vibration amplitudes along each major crystalline direction, and occupation lengths of channeled positrons and electrons; (b) defects and impurities in imperfect crystals, such as the location and extent of platelets in diamond; and (c) factors facilitating or limiting the use of channeling radiation as a photon source, such as radiation damage in both silicon and alkali-halide crystals and the dependence of radiation intensity on crystal species and thickness. A recent monograph by Kumakhov and Wedell[8] constitutes a comprehensive review of most of the literature, both theory and experiment. Results from the superconducting linacs at Darmstadt and Stanford show[9] that the intensity of channeling radiation (but not necessarily its spectral shape) scales linearly with electron beam current, at least up to 60 μA. These results certainly augur well for the feasibility of channeling radiation as an intense radiation source for applications, but do not provide evidence for predictions of nonlinear effects. Very recent results from Darmstadt at even higher beam currents have extended the linear range in the low-energy region.[10]

Planar channeling radiation from diamond at low incident electron energies (tens of MeV) illustrates the transition from the quantum regime, where individual transitions between well-separated discrete states can be seen clearly, to the classical regime, where the number of bound states and hence the number possible transitions increases, resulting in spectral lines of increasing width and decreasing spacing. Figure 1 shows data obtained at Saclay[4] that illustrates this transition. As the energy increases further, the identity of the individual spectral lines is lost, and the measured spectrum becomes a "bump," composed of the superposition of many lines.

At the high energies now available at Jefferson Lab, from a few hundred MeV to a few GeV, prior data are sparse. A few examples are given here, partly to show what has been achieved and partly to emphasize how much the field is in need of new high-quality data. Figure 2 shows the energy dependence of planar channeling radiation from diamond obtained at Tomsk.[11] Figure 3, showing data from Yerevan,[12] illustrates the thickness dependence for diamond at high energies. Figure 4, also showing Yerevan data, illustrates the evolution from axial to planar channeling as the crystal is rotated. Figure 5 shows data obtained by the Aarhus group at CERN[13] for 6.7-GeV positrons and electrons in silicon, illustrating the relativistic harmonic bump (part a) at twice the energy of the "classic" bump due to the harmonic potential itself for positrons; electrons for which the potential is cusp-shaped rather than harmonic shows no such bump (part b). Finally, Fig. 6 shows CERN data[14] for the thickness dependence for high-energy positrons in both silicon and germanium crystals.

At high energies, however, there are some tantalizing data that indicate the presence of nonlinear effects. Whereas all other coherent-radiation experiments at GeV energies have been carried out with low electron beam intensities, Aganyants *et al.*[15] observed anomalously low energy loss of 4.5-GeV electrons channeled very close to the axes or planes of diamond, and anomalous broadening[16, 17] of the angular distribution of channeling radiation (up to an angle of $6/\gamma$) when the electron beam intensity was relatively high. This broadening is seen at all photon energies, from 0.2 to 4.0 GeV, and, most remarkably, at 0.3 GeV, actually becomes resolvable into two peaks, as is shown in Fig. 7.[17] Anomalous angular broadening was seen earlier for the case of coherent bremsstrahlung as well.[18] These anomalies can be interpreted to result from a strong-field process taking place in a region of the crystal volume where a large fraction of the atoms are in an excited state, owing to the pumping effect induced by the energy loss of previous beam electrons, a kind of quantum-electromagnetic medium effect. This is plausible if the lifetime of these excited states is of the order of nanoseconds and the beam flux is of the order of 100 nA/mm^2. However, the interpretation of these data is uncertain because of the relatively low rate capability of the scintillation counter used, the multiple passes through the target made by the beam in the circular accelerator used, and insufficient intensity and control of the electron beam. All of these disadvantages can be rectified at Jefferson Lab: we propose to overcome them by using a detector system with many narrow scintillators, requiring only a single pass through the crystal target, and using the excellent emittance and control of the CEBAF beam.

Proposed Experimental Measurements

For our initial set of experimental measurements, we propose to vary four experimental parameters: (1) the electron beam energy over a factor of about 1.7 (a factor of 3 in γ^2), by using beams of 3.3, 4.4, and 5.5 GeV; (2) the beam current over a factor of 100, by using beams of 1.5, 5, 15, 50, and 150 nA; (3) the diamond crystal thickness, by using two different crystals, having thicknesses of 100 and 500 μm; and (4) the energy density deposited in the crystal by using three different values for the beam-spot diameter (*e.g.*, a change from 1 mm to 0.3 mm increases the energy density, and presumably the medium effect, by an order of magnitude). In order to measure the energy loss of the scattered electrons to test whether the distribution of energy losses is anomalously small, we plan to instrument the cross in the Tagger beam-dump line with scintillating fibers capable of position resolution of the order of 0.2% of the incident beam energy (*e.g.*, 10 MeV at 5 GeV), consistent with the somewhat enlarged beam size at this location resulting from multiple scattering in the crystal (~6 mm). The location of this cross is shown in Fig. 8.[19]

The channeling radiation itself will be detected by the new beam-profile detector system, consisting of a thin converter plate backed by two banks of scintillator strips 64 mm long by 2mm by 2mm, made of double-clad scintillating fibers, so that for both horizontal and vertical planes, the array is about 12.8 cm square. Each plane of 64 detectors will be read out by four multi-anode Hamamatsu R5900-00-M16 photomultiplier tubes. This detector array will be positioned about 60 m downstream of the diamond crystal radiator, so that it subtends an angle of $5/\gamma$ for the 2.5-GeV case and $12/\gamma$ for the 5.5-GeV case. The angular resolution is thus of the order of $1/4\gamma$. The first detector array of this kind was just commissioned, and is shown in Fig. 9.[20]

The goniometer was designed for coherent-bremsstrahlung production of a polarized photon beam and has been newly built and commissioned. It has five degrees of motion, including pitch, yaw, and roll angles, and several targets can be mounted simultaneously and moved into the beamline remotely. Its angular resolution is of the order of 0.04 mrad, a factor of two smaller than $1/\gamma$ for 6 GeV. In its very first commissioning run, a coherent-bremsstrahlung spectrum from a diamond crystal was observed, which is shown in Fig. 10.[21]

Electron-beam monitoring will be done with the usual beam-position monitors, which are capable of functioning over a very large range of beam currents, down to 100 pA, with better than 100-μm spatial resolution. Photon beam normalization will be done with the usual lead-glass Total-Absorption Counter at low photon fluxes, and with the Pair Spectrometer and Pair Counter at high fluxes. No beam collimator will be used.

The GW group played a major role in the design, construction, installation, and commissioning of both the Tagger focal-plane detector array[19] and the goniometer.[21] The beam-profile array is a product of the Jefferson Lab Detector and Fast Electronics groups.[20] The diamond crystals will be supplied by the Yerevan group.

Beam Quality and Beamtime Requirements

In order to accomplish our goals, the requirements for the properties of the electron beam are: (a) energy spread less than 0.03%; (b) angular divergence less than 0.05 mrad (for 5.5 GeV); and (c) variable spot size from 0.1 to 1.0 mm. As far as we know, these parameters are well within the advertised specifications of CEBAF.

Under these conditions, the signal (channeling radiation) should exceed the background (incoherent bremsstrahlung) by a factor of 20 or more.[13]

As detailed in the previous section, we intend to vary four parameters, so that we have 90 data-production runs, plus about 12 background runs (no crystal and amorphous radiator for the three energies and for both medium and high currents). Although the production runs will take very little time (the cross sections are megabarns!), there is quite a bit of overhead. Also, we shall undoubtedly want to repeat some of the low-intensity runs after performing the high-intensity runs, just to make sure that the diamonds have not suffered any warping or other damage (which could masquerade as a nonlinear effect!). We estimate that setup time with beam (not counting initial beam-tuning) will require about 1.5 days and that production and background runs will require about 5.5 days, for a total of 7 days.

References

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13. M. Atkinson *et al.*, Phys. Lett. **110B**, 162 (1982).

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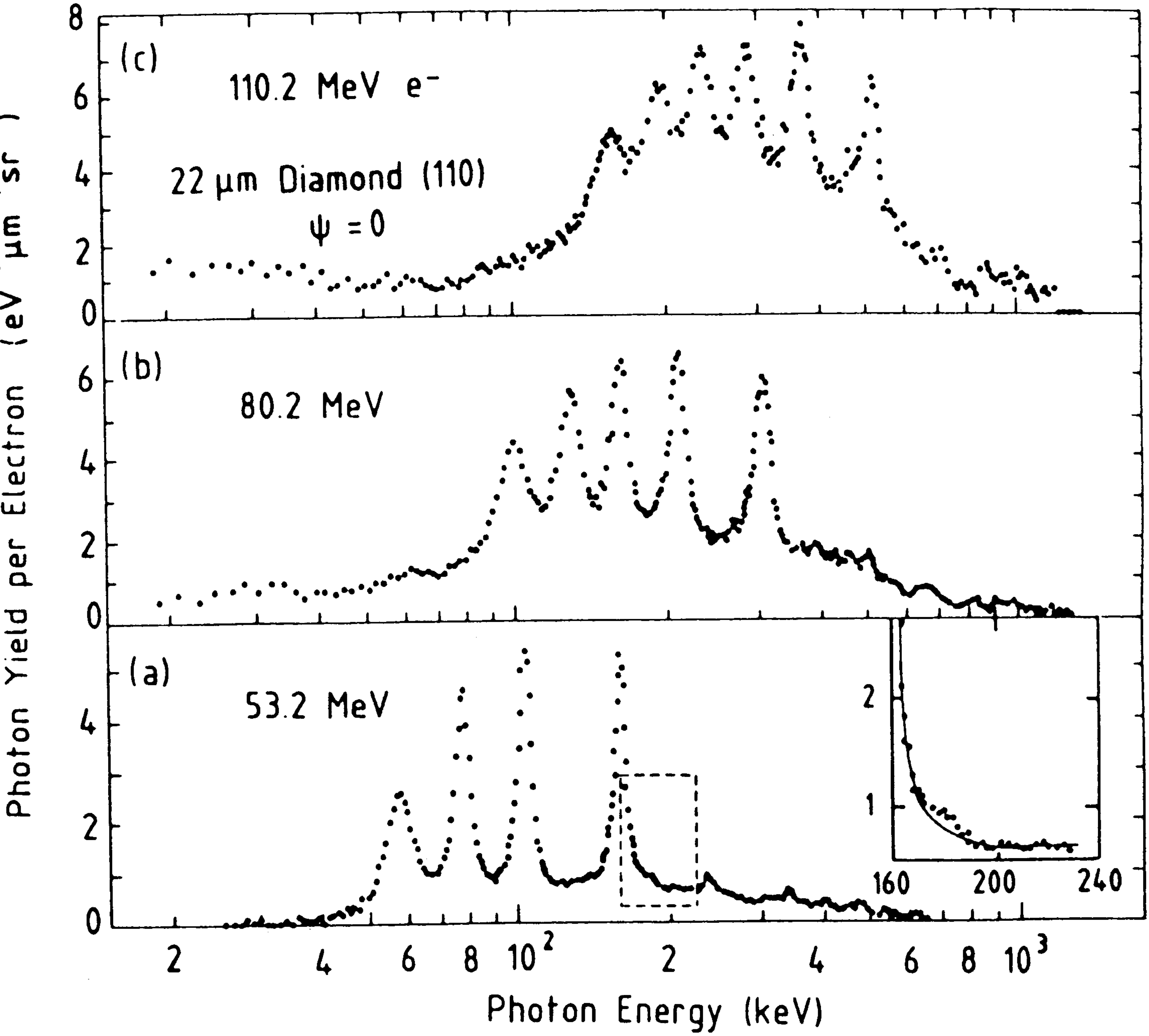


Figure 1. Channeling radiation as a function of incident electron energy for modest energies (Saclay data).

Diamond (110)

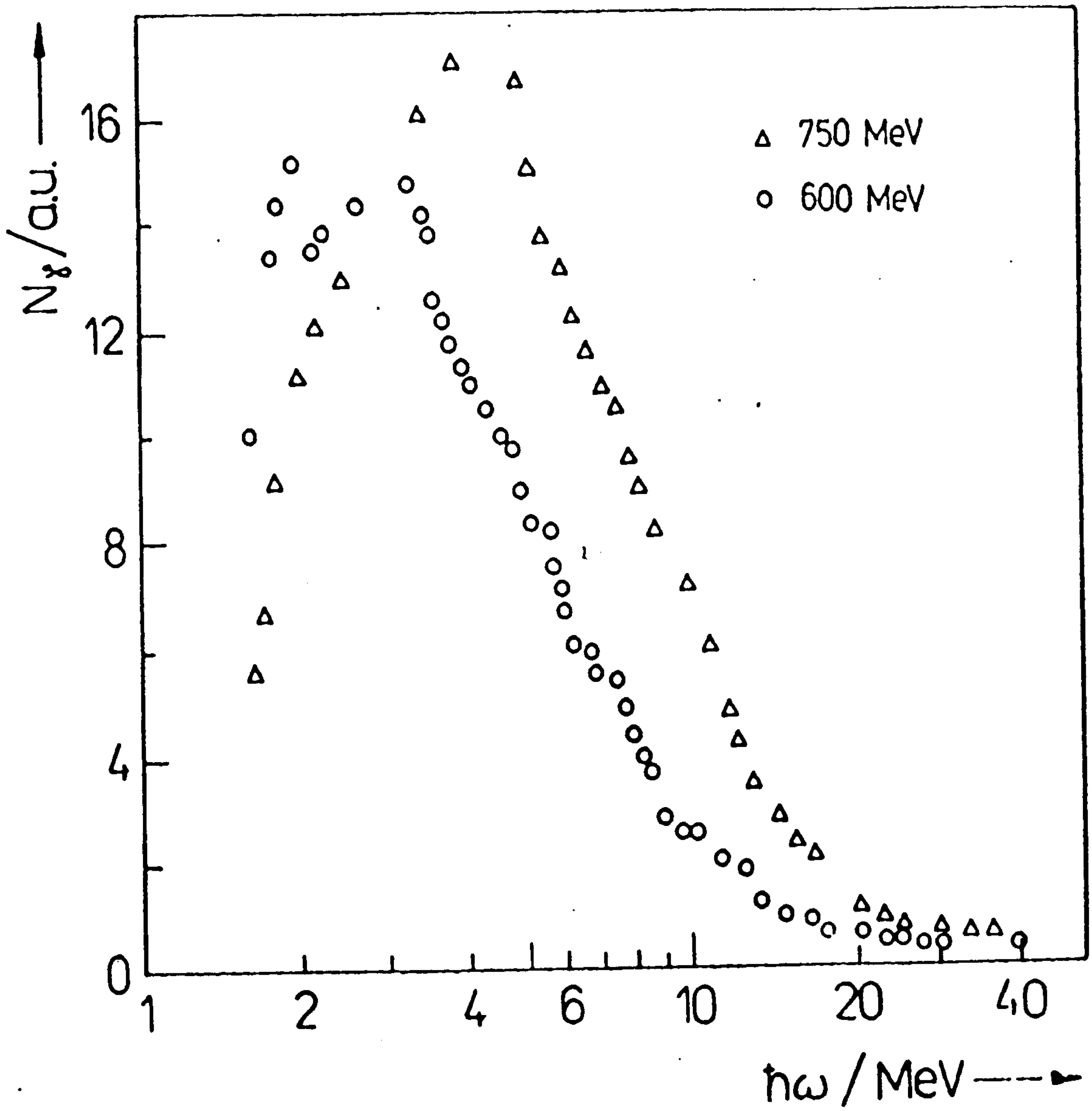


Figure 2. Channeling radiation for two medium energies (Tomsk data).

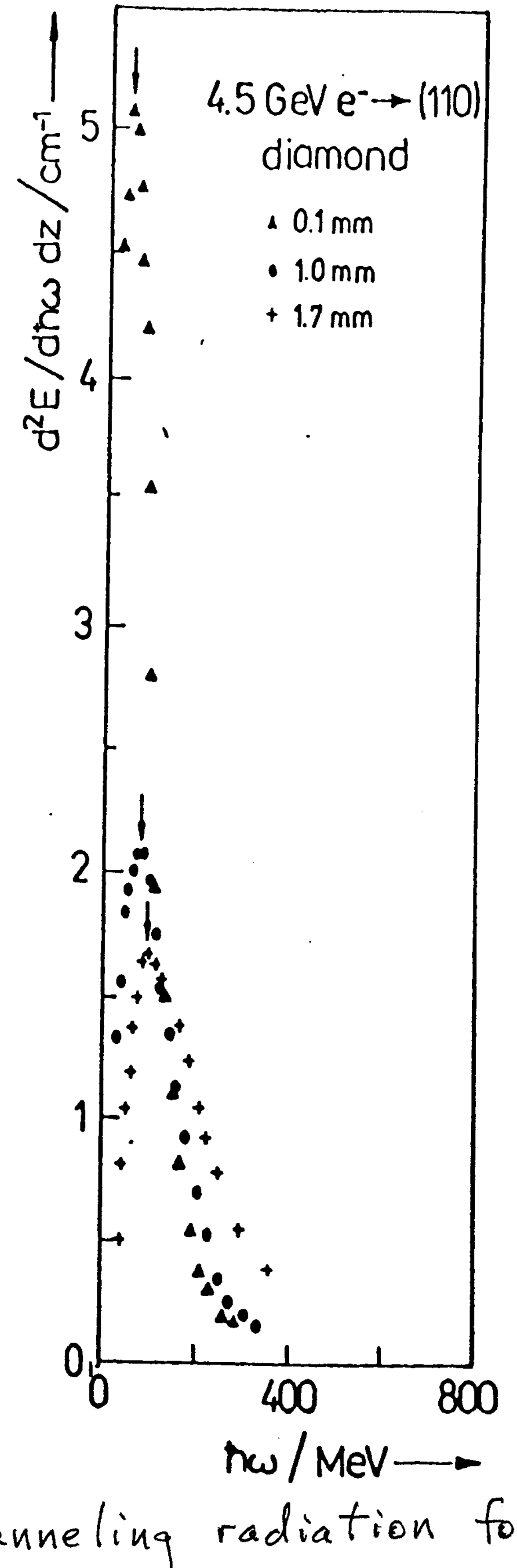


Figure 3. Channeling radiation for high energy as a function of crystal thickness (Yerevan data).

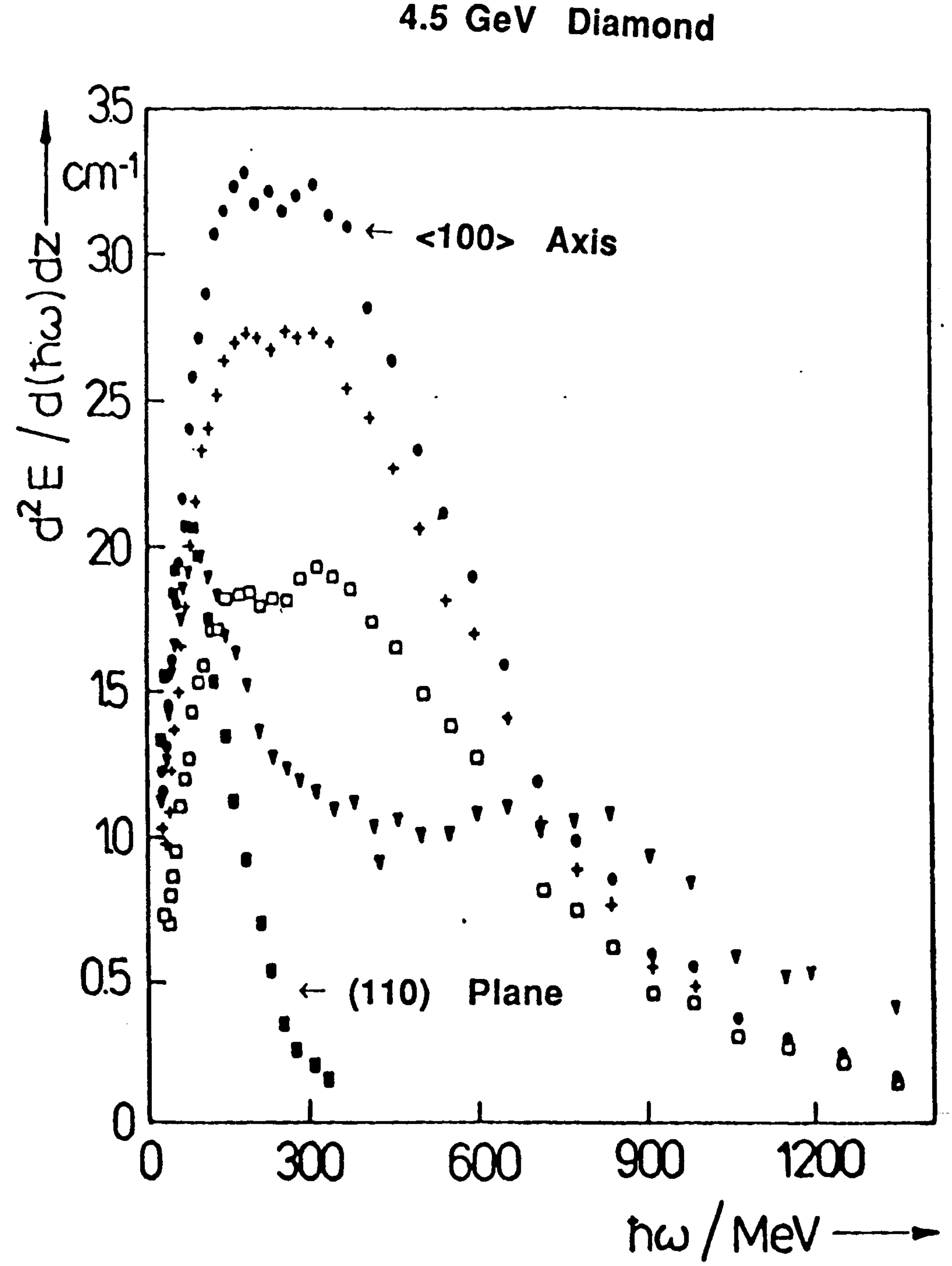


Figure 4. Evolution of channeling radiation for high energy from planar (110) to axial <100> (Yerevan data).

6.7 GeV

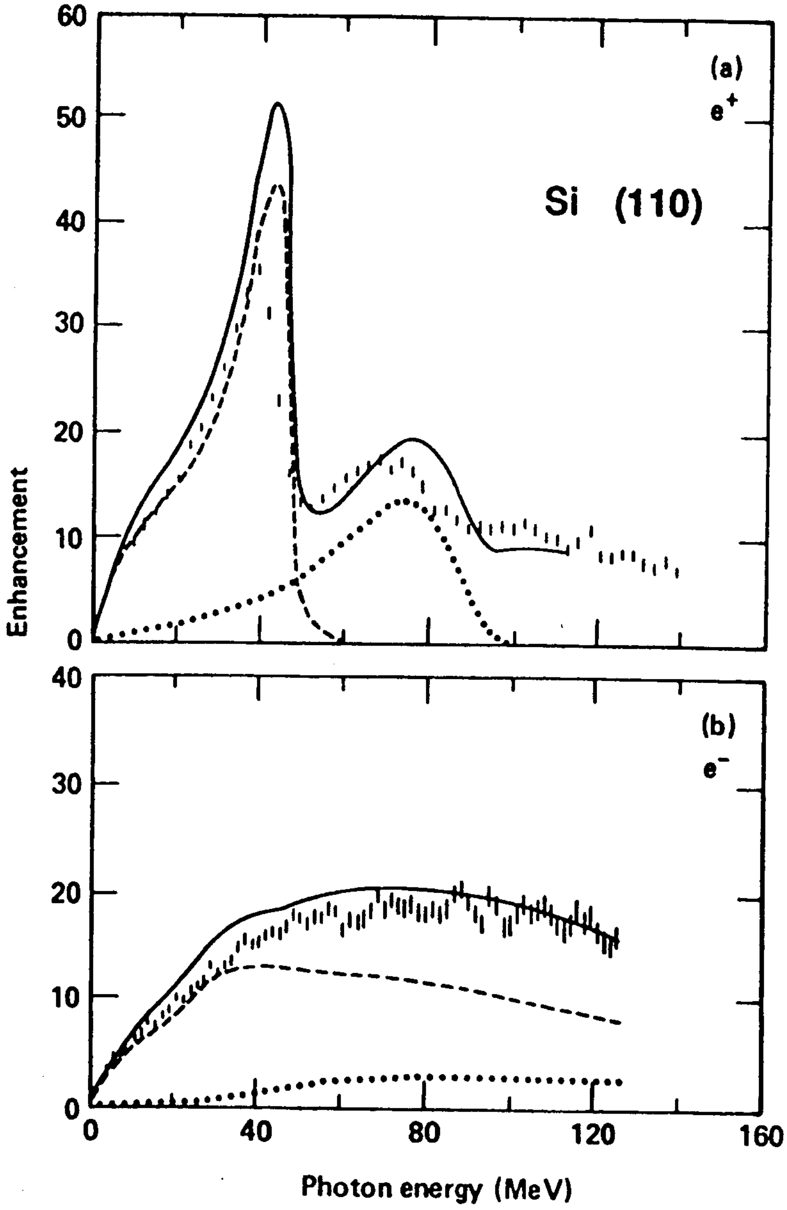


Figure 5. Comparison of channeling radiation for high-energy positrons and electrons (CERN data).

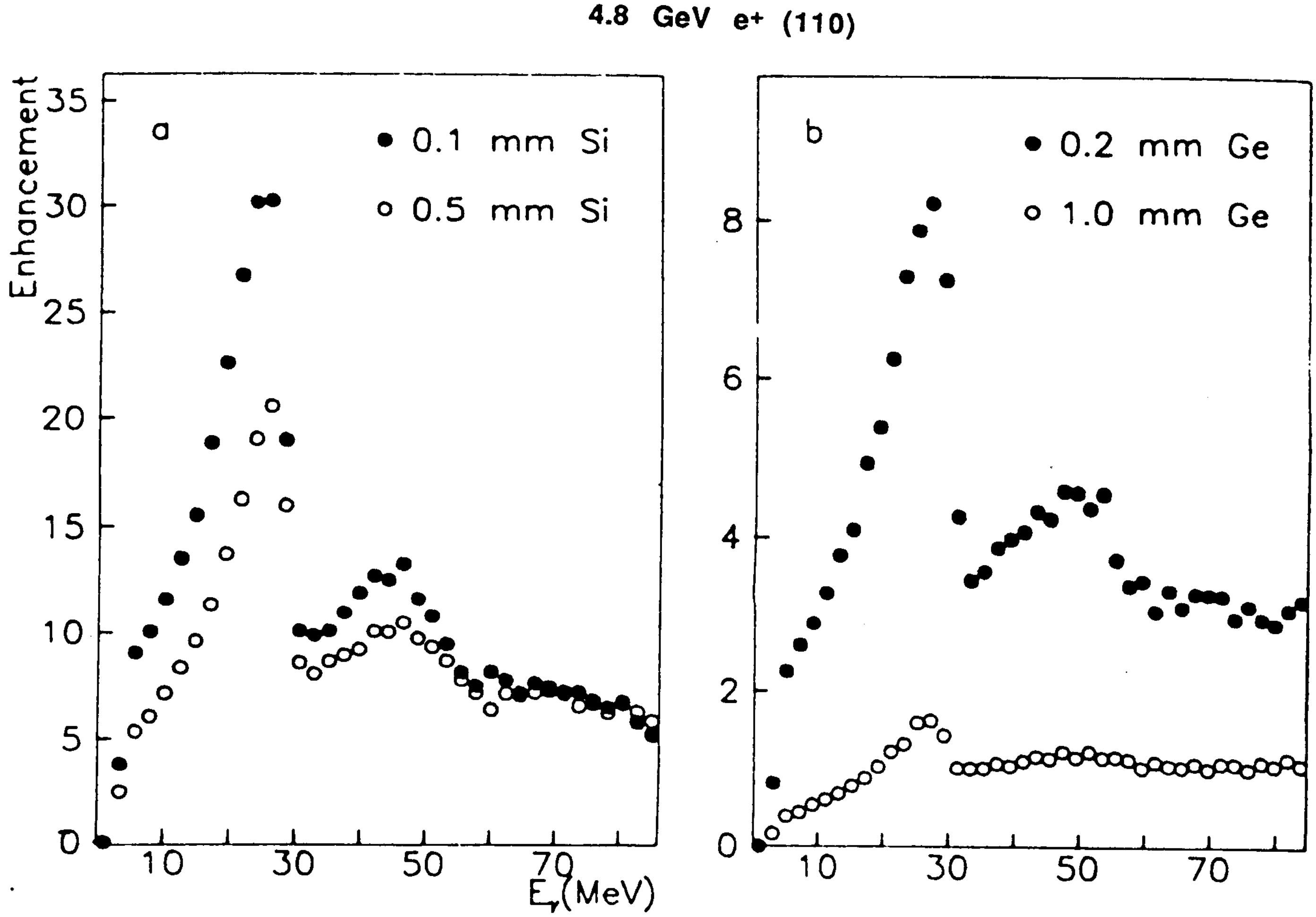


Figure 6. Thickness dependence of high-energy channeling radiation for positrons (CERN data).

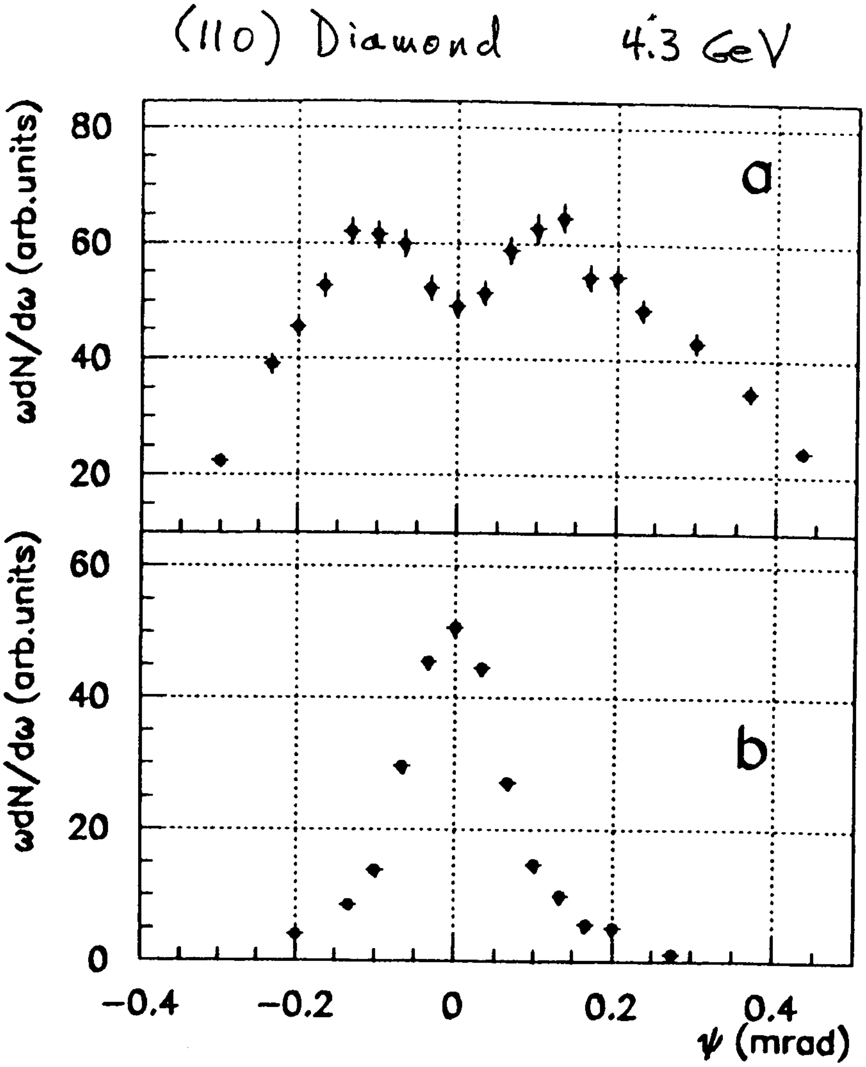


Figure 7. Anomalous splitting of channeling radiation for emission angles ψ (a) perpendicular and (b) parallel to the (110) plane (Yerevan data).

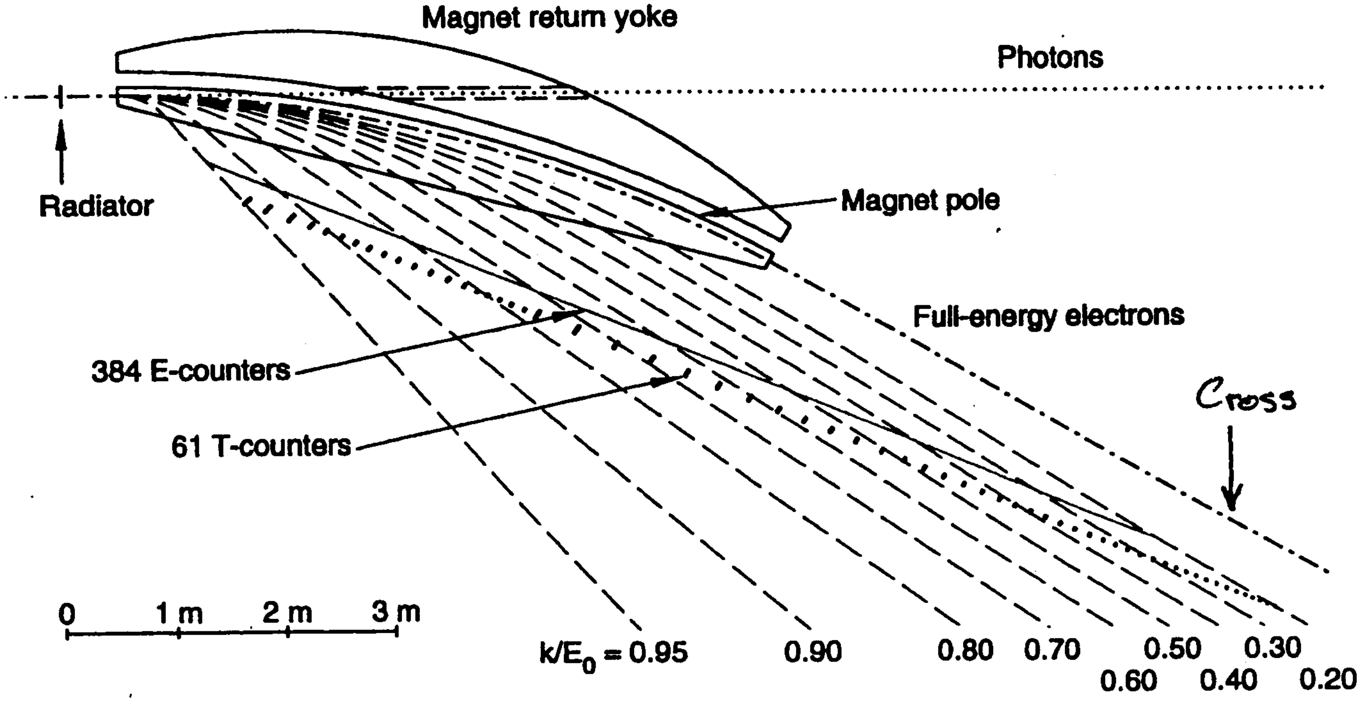
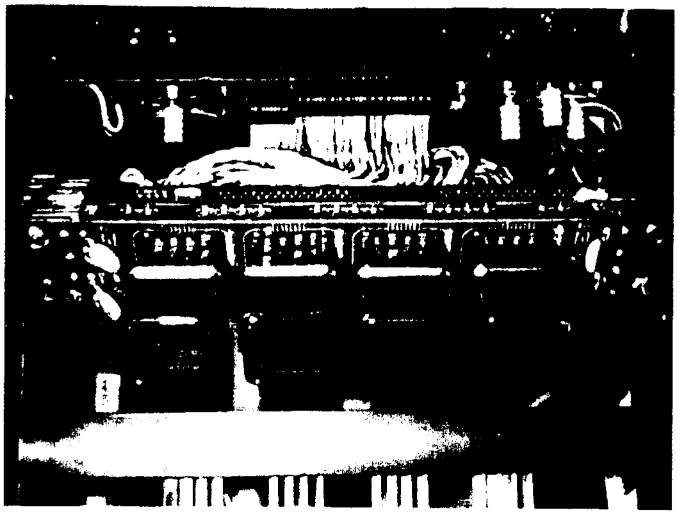


Figure 8. The Hall-B Photon Tagger with the approximate position of the cross noted.



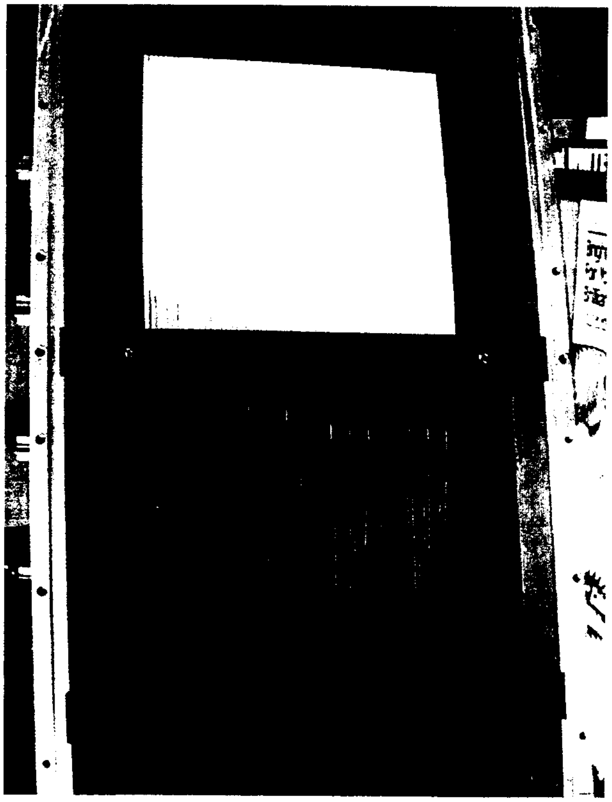


Figure 9. Scintillating-fiber photon-beam profiler: (top) Multi-anode PMTs with readout boards; (bottom) Fiber module showing scintillating fibers (white) and light-guide fibers (clear). (JLab Detector and Fast Electronic Groups)

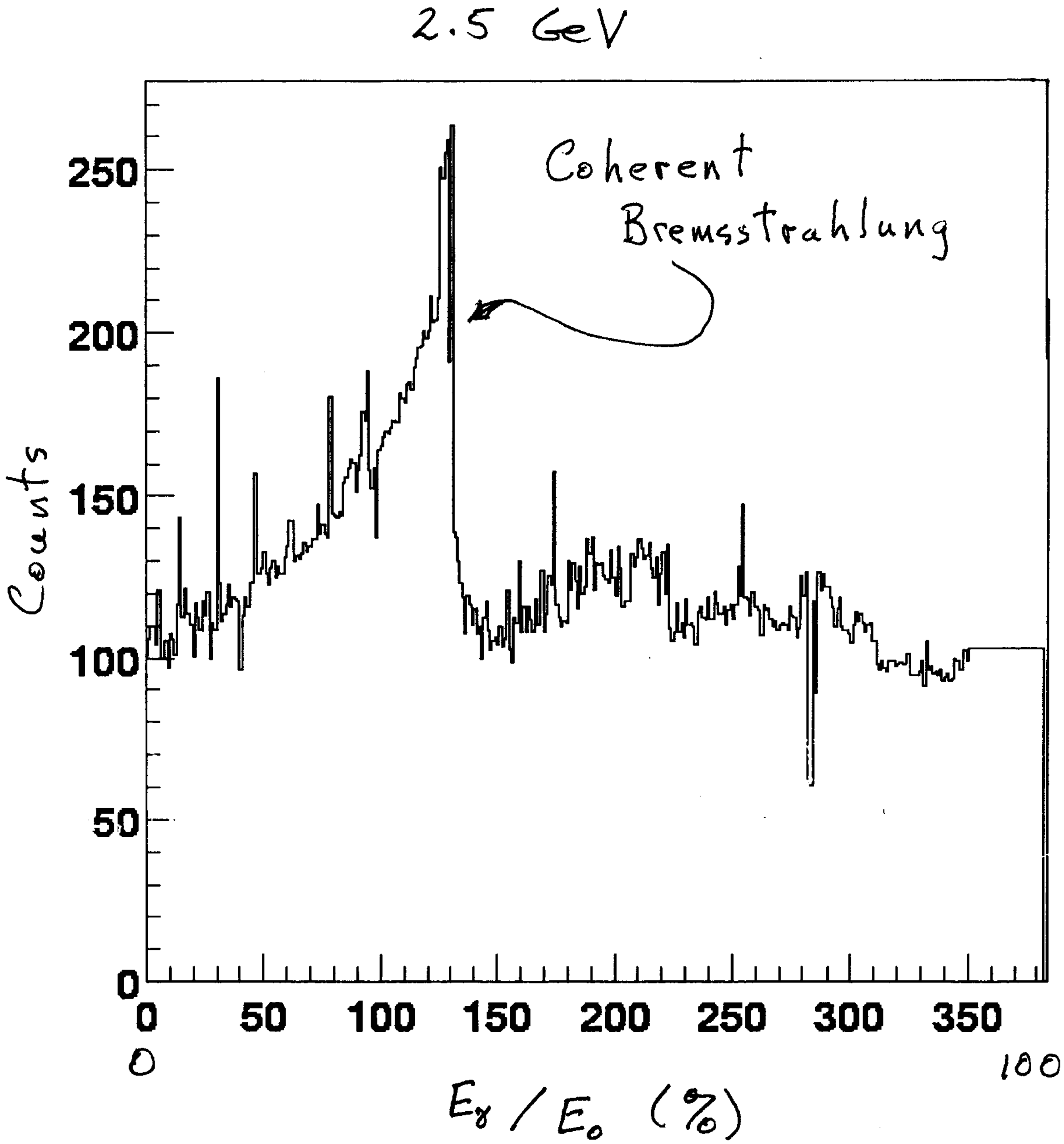


Figure 10. Coherent bremsstrahlung spectrum from a diamond crystal mounted in the GWU/JLab goniometer.